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A METHOD FOR THE CALCULATION OF TOLERANCES FOR DISPLAY PRIMARY CHROMATICITY COORDINATES

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Summary

The manufacturers of displays for television and other visual display systems are rarely given sufficient information to ensure that their products perform satisfactorily. Typically, parameters such as the peak brightness and primary chromaticities, transfer characteristic and illumination uniformity are supplied, but this information is usually generic, it does not refer specifically to the display in question.

There is no internationally accepted method for defining the tolerances of primaries. A study was made of the tolerance zones for the EBU primaries, with the aim of developing a strategy which might work successfully on other standards. As a result of this study, a method has been developed, and a proposal made for tolerance zones for the primaries specified in ITU-R Recommendation BT. 709.

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A METHOD FOR THE CALCULATION OF TOLERANCES FOR DISPLAY PRIMARY CHROMATICITY COORDINATES

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1. INTRODUCTION

Correction for wrongly coloured primaries is possible in the display[1] but is rarely wholly successful. A better solution to the problem of incorrect primaries is to define an acceptable tolerance for each primary, so that imperfect displays can be used without requiring correction. Clearly, the tolerances must be set such that any display meeting them is subjectively acceptable. Tolerances are needed by display manufacturers and equipment buyers alike, in order to guarantee an acceptable degree of colorimetric uniformity of displays.

There is no internationally agreed standard method for calculating the acceptable tolerances for display primary chromaticity coordinates. The tolerance zones specified for the EBU primaries, as disclosed in EBU Tech. 3213[2] have served well for many years and compliance has proved to be possible by most display manufacturers, but their origins are dubious and seem to have little to do with colorimetry.

The tolerances for the EBU primaries have been achievable in Grade 1 monitors for many years. Thus there is no practical or commercial reason for either tightening or loosening the tolerances which should apply to the new ITU-R Recommendation BT. 709[3]* primaries. However, any new specification of tolerances should be based on sound colorimetric principles and not on any surmise about possible developments in display technology, particularly at a time when completely new types of display are being developed.

This Report investigates colorimetrically-sound calculation procedures for specifying tolerance zones. Many different criteria could be used, and so a preliminary examination of the tolerances specified by the EBU was conducted with some success. Using the techniques thus derived, a proposal for a set of tolerances for the Rec. 709 primaries has been calculated.

2. INVESTIGATION

The EBU primaries were formalised in the early 1970's, and tolerance zones for them were given without reference to any formal work. There are hints in Tech. 3213 that work on this was undertaken in the United Kingdom jointly by the BBC and the display industry, but there are no specific references to such work. No archival evidence has been found relating to work done at BBC Research Department, and sadly most of the workers in the field at that time have long-since retired or died. It seems most likely that the tolerance zones were arrived at as a result of the manufacturers reporting on the consistency with which they could supply phosphors, but probably without rigorous analysis of the colorimetric consequences.

Having failed to find a colorimetrically satisfying explanation for the tolerance zones given, a mathematical investigation was carried out in an attempt to redefine tolerances which resemble those of Tech. 3213 using sound colorimetric techniques, with some success.

2.1 The EBU primaries

The primaries[4,5] and white point (at which the drive signals, R G B, are all equal) are specified in Table 1 in the CIE 1931 system:

Table 1: EBU display primary chromaticities.

	x	y
Red	0.64	0.33
Green	0.29	0.60
Blue	0.15	0.06
D_{65}	0.313	0.329

The intrinsic tolerances were specified "in 1970 after a thorough examination of the colorimetric characteristics of phosphors available at that time and after discussions with the manufacturers on likely developments". The tolerance boxes are given as quadrilaterals with vertices as follows[2] and are shown on chromaticity diagrams in CIE 1931, 1960 and 1976 colour

Table 2: EBU primary tolerance box vertex chromaticities.

	x_1	y_1	x_2	y_2	x_3	y_3	x_4	y_4
Red	0.654	0.332	0.640	0.319	0.608	0.322	0.637	0.349
Green	0.320	0.605	0.286	0.542	0.280	0.610	0.298	0.627
Blue	0.158	0.060	0.150	0.053	0.143	0.061	0.154	0.072

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* Although now known by ITU (International Telecommunications Union) Radiocommunications Sector designations, the Recommendations were first published as CCIR Recommendations.

spaces.† Clearly, the tolerance box 1960 vertices do not align with the axes of any of these commonly used colour spaces, and indeed there is no known reason why they should.

A skin-tone test colour was also specified for analysis purposes.[2,6] For consistency within this document, it is given here converted to CIE 1931 *xy* chromaticity coordinates. Skin tones are widely recognisable colours, and are frequently used for critical alignment of cameras and displays.

Table 3: Test colour.

	Y	x	y
Skin tone	0.4404	0.3622	0.3540

2.2 Investigation of EBU primary tolerances

A search was made to find a colorimetrically sound mathematical method for defining the existing EBU tolerances, with the intention of adopting it as a method for calculating tolerances for the Rec. 709 primaries (if such a colorimetric formula can be found to reproduce the EBU tolerances, then that formula can be translated for use on any other set of primaries to the same effect).

2.2.1 Calculation methods

Two techniques were tested:

- Single primary intrinsic tolerance. Move the chromaticity of each primary in turn (the other two being irrelevant, but fixed at their target chromaticities) to produce erroneous reproduction of that primary by a fixed amount. This represents the greatest visual error that a single erroneous primary can generate.
- Single primary extrinsic tolerance. Move the chromaticity of each primary in turn (other two fixed at their target chromaticities) such that skin-tone reproduction erred by a smaller fixed amount.

It was suspected that a combination of the these techniques might go some way towards reproducing the EBU tolerance boxes and provide the basis for a suitable method. Since they calculate the appearance of errors in one primary at a time, there needs to be a method for assessing the effects of errors in all three primaries, but only if the individual primaries are imperfect.

A third technique was also described in the EBU documents,[2,6] albeit almost as an afterthought, but was not tested at this stage:

- Primary triad extrinsic tolerance. Analyse the skin-tone reproduction for the set of three primaries, either mathematically or using a graphical approximation technique.

An alternative, and simpler, approach to this problem is dicussed in Section 3.2.

Five colour error spaces were each explored, although only the first would have been available to researchers at the time of specifying the tolerances for the EBU primaries:-

- Just Noticeable Differences in CIE 1960 (chrominance only)
- Just Noticeable Differences in CIE 1976 (chrominance only)
- CIELuv δE^*
- CIELab δE^*
- CMC δE^*[7]

The skin tone test colour used in this exploration was that specified in Tech. 3213 in the section entitled ‘Tolerances for skin-tones’. It was required that the reproduction of the skin-tone should have a chromaticity error of not greater than a radius of 0.003 in the CIE 1960 chromaticity diagram (approximately 1 jnd), irrespective of luminance errors and intrinsic errors in the primaries.

2.2.2 Results of investigations

All five colour error spaces were investigated for both intrinsic and single-primary extrinsic errors, resulting in 30 explorations. All error space calculations produced basically similar results. Intrinsic tolerance calculations produced a distorted ellipse centred on each primary. Extrinsic tolerance calculations produced a projection of a distorted ellipse whose major axis was usually aligned with the vector joining the primary and the test colour in the chromaticity diagram. By selecting the target colour error magnitudes individually for each primary for each calculation, these ellipses could be made to intersect each other such that the common area somewhat resembled the existing tolerance boxes. This process was moderately successful in all five colour error spaces. However, when allowing only one target error magnitude to be used for the set of three primaries, the calculations were much less successful.

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† Only the 1931 and 1960 diagrams would have been available to workers at the time of this specification, but it is known that various distorted forms of chromaticity diagram had been developed for specific purposes.

None of the error calculations satisfactorily reproduced the EBU tolerance boxes but some interesting results were obtained. Figs. 1 to 5† show the calculated results for the five colour error spaces, with calculations for each primary for both intrinsic and extrinsic tolerance. The results are all shown on CIE 1931 *xy* chromaticity diagrams, all plotted to the same scale. Admittedly, this is a psychometrically non-uniform diagram but, since the primaries are specified in CIE 1931 terms, it was thought best to study tolerances specified in the same space. The error magnitudes were chosen such that the resulting overlapping zones each had areas which most closely resembled the EBU tolerance zones in terms of area; but it was not possible to choose error magnitudes to reproduce the shapes as well.

CIE 1960 chrominance jnds: (intrinsic error = 0.2, extrinsic error = 2.0) It was not possible to specify, for the two methods, error magnitudes which produced overlapping tolerance zones which even remotely resembled the EBU boxes. The green ellipses could not be made to intersect each other at all for sensible error magnitudes.

CIE 1976 chrominance jnds: (intrinsic error = 0.2, extrinsic error = 3.0) This was marginally better than CIE 1960, but it was still not possible to mimic the areas of the EBU boxes. Similarly, the green ellipses could not be made to intersect for sensible error magnitudes.

CIELuv δE^*: (intrinsic error = 1.0, extrinsic error = 6.0) Red and green zones were smaller and blue larger than the EBU boxes. The basic shape of the blue box bore a slight resemblance to that of the EBU box.

CIELab δE^*: (intrinsic error = 0.75, extrinsic error = 8.0) The blue and red zones had acceptable shape and size but were skewed, and the green zone was considerably smaller than the EBU box.

CMC(1:1) δE^*: (intrinsic error = 1, extrinsic error = 4.0) the red and blue zones were skewed but of similar size and shape, and the green zone was similar in size but misplaced relative to the EBU box.

The colour error spaces could be ranked by performance in the reverse of the order in which they are reported here. CMC is 'best' but is not dramatically better than the others. Any of CIELuv, CIELab and CMC could be used, but CMC produced the closest match in both size and shape to the old EBU tolerance boxes. Varying the luminance/ chrominance weighting between 10:1 and 1:10 in the calculation process did not significantly alter this conclusion.

The CMC system is a more recent development from the CIELab system, having an infinite number of error spaces (one for each specifiable colour) that are supposedly better matched to the real performance of the average human eye. It is thus the most likely error space to produce results that match the colour discrimination ability of human vision. Fortunately, the overlapping of the ellipses resulted in shapes which could be defined fairly accurately as quadrilaterals, thus removing the need to specify curved lines.

3. APPLICATION OF THE METHOD TO REC. 709 PRIMARIES

The primaries and white point are specified as follows in the CIE 1931 system, only the x coordinate of the green primary is different from the EBU values:

Table 4: Rec. 709 display primary chromaticities.

	x	y
Red	0.64	0.33
Green	0.30	0.60
Blue	0.15	0.06
D_{65}	0.313	0.329

3.1 Intrinsic and extrinsic primary tolerances

Using the CMC(1:1) error space and colour error values established for the EBU primaries investigation ($\delta E^* = 1.0, 4.0$), the calculations were repeated for the display primaries of Rec.709 and the results are shown in Fig. 6. Due to the intersecting nature of the ellipses, the 'sides' are not particularly curved and so it is possible to simplify the specification of these zones into irregular quadrilaterals. By inspection, these can be defined (to three significant figure accuracy) as shown in Table 5 *(overleaf)*.

Using values specified to only three significant figures produces quadrilaterals which inevitably deviate from the strict colorimetric reasoning behind the values tabulated, but more precision would not be of any great benefit in defining tolerances.

3.2 Extrinsic tolerances for the set of primaries

It was felt that a simple means could be developed for assessing the extrinsic accuracy of the set of primaries. In the case of the EBU tolerance box specification, this required the additional calculation (or prediction by

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† All Figures are at the end of this Report.

Table 5: 709 tolerance zone vertex chromaticities.

	x, y vertex 1	x, y vertex 2	x, y vertex 3	x, y vertex 4
Red	0.609, 0.340	0.633, 0.342	0.670, 0.318	0.642, 0.318
Green	0.285, 0.641	0.314, 0.619	0.310, 0.560	0.289, 0.569
Blue	0.145, 0.066	0.163, 0.0704	0.154, 0.0534	0.136, 0.0507

Table 6: 709 inner tolerance zone vertex chromaticities.

	x, y vertex 1	x, y vertex 2	x, y vertex 3	x, y vertex 4
Red	0.620, 0.333	0.646, 0.333	0.657, 0.326	0.630, 0.326
Green	0.296, 0.617	0.305, 0.617	0.305, 0.583	0.296, 0.583
Blue	0.151, 0.0678	0.157, 0.0691	0.148, 0.0526	0.142, 0.0516

Table 7: 4-figure outer-tolerance zone vertices.

	u′, v′ vertex 1	u′, v′ vertex 2	u′, v′ vertex 3	u′, v′ vertex 4
Red	0.4154, 0.5223	0.4345, 0.5271	0.4898, 0.5223	0.4640, 0.5172
Green	0.1127, 0.5699	0.1280, 0.5685	0.1362, 0.5538	0.1244, 0.5536
Blue	0.1654, 0.1708	0.1855, 0.1802	0.1853, 0.1443	0.1627, 0.1367

Table 8: 4-figure innter tolerance zone vertices.

	u′, v′ vertex 1	u′, v′ vertex 2	u′, v′ vertex 3	u′, v′ vertex 4
Red	0.4299, 0.5203	0.4537, 0.5258	0.4713, 0.5242	0.4444, 0.5189
Green	0.1203, 0.5658	0.1243, 0.5669	0.1300, 0.5590	0.1260, 0.5580
Blue	0.1722, 0.1747	0.1795, 0.1780	0.1767, 0.1425	0.1704, 0.1365

graphical means) of the colour appearance of the skin-tone test colour. As an alternative, it may be desirable to specify a second, but tighter, set of tolerance zones, within which any set of primaries would give acceptable skin-tone reproduction irrespective of the primary errors. At worst this requires an infinite number of calculations, on every possible combination of primary chromaticities within the intrinsic tolerance zones. For example, simply placing the primaries at the extremes (vertices) of the intrinsic tolerance zones in every possible combination requires 64 calculations. This revealed that the reproduction error of the test colour ranges from 0.2 δE* to 3.7 δE* measured in CMC(1:1) units. Clearly, with such a large range of errors, it is impossible to subdivide the tolerance zones *accurately* into smaller 'safe' and 'dubious' zones.

However, it is possible to specify an inner zone within each intrinsic tolerance zone, such that the reproduction error for the test colour never exceeds 1/3 δE* for each primary. Then, if the three primaries each fall within these inner zones, the reproduction error is unlikely to exceed 1 δE*, and further analysis is unneccessary. The inner zones are ellipses, concentric with the 1 δE* zones already calculated, and are shown in Fig. 7. In the cases of the Red and Blue primaries, these inner ellipses intersect the tolerance zones already defined in such a way that they can also be represented by quadrilaterals. The Green inner ellipse is significantly smaller than the outer zone, but can still be approximated by a quadrilateral. These approximations are shown in Fig. 8 and the vertices of the inner zones are shown in Table 6 (again to three significant figures).

The values thus calculated and tabulated in Tables 5 and 6 form a proposal for the tolerances of the display primaries for ITU-R Rec. BT. 709. The full proposal, for outer and inner tolerance zones, is shown in Fig. 8.

For completeness, it may be useful to tabulate the chromaticity coordinates in the more usual CIE 1976 u′v′ colour space. The values in the previous tables were calculated from the x,y values before restriction to 3 significant figures and are given to 4-figure accuracy in Tables 7 and 8. These values should not be used for further conversion into other spaces; it is recommended that only these two sets be used for practical purposes, with preference given to the x,y values.

4. CONCLUSION

A method has been established for calculating acceptable tolerance zones for display primary chromaticities, using sound colorimetric techniques. Application of the method has lead to a proposal for tolerance zones for the display chromaticity coordinates of the ITU-R Rec. BT. 709 primaries.

5. REFERENCES

1. LENT, S.J., REED, C.R.G., *and* STOREY, R., 1977. Correction of primary chromaticities of display tubes by matrixing of gamma-corrected RGB signals. BBC Research Department Report No. RD 1977/17.
2. EBU, 1975. Standard for Chromaticity Tolerances for Studio Monitors. Tech. 3213, August.
3. CCIR Recommendation 709, 1990. Basic parameter values for the HDTV standard for the studio and for international programme exchange.
4. BBC & ITA, 1971. Specification of Television Standards for 625-line System-I Transmissions. January.
5. Characteristics of television systems. 1990. CCIR Report 624-4.
6. TAYLOR, E.W., 1972. A rapid graphical method of evaluating the chromatic properties of a television tube. BBC Research Department Report RD 1972/30.
7. TAYLOR, E.W., 1974. Colour Television Displays: error diagrams for evaluating the reproduced chromaticities of some test colours. BBC Research Department Report RD 1974/34.
8. British Standard BS6923, 1988. The calculation of small colour differences.

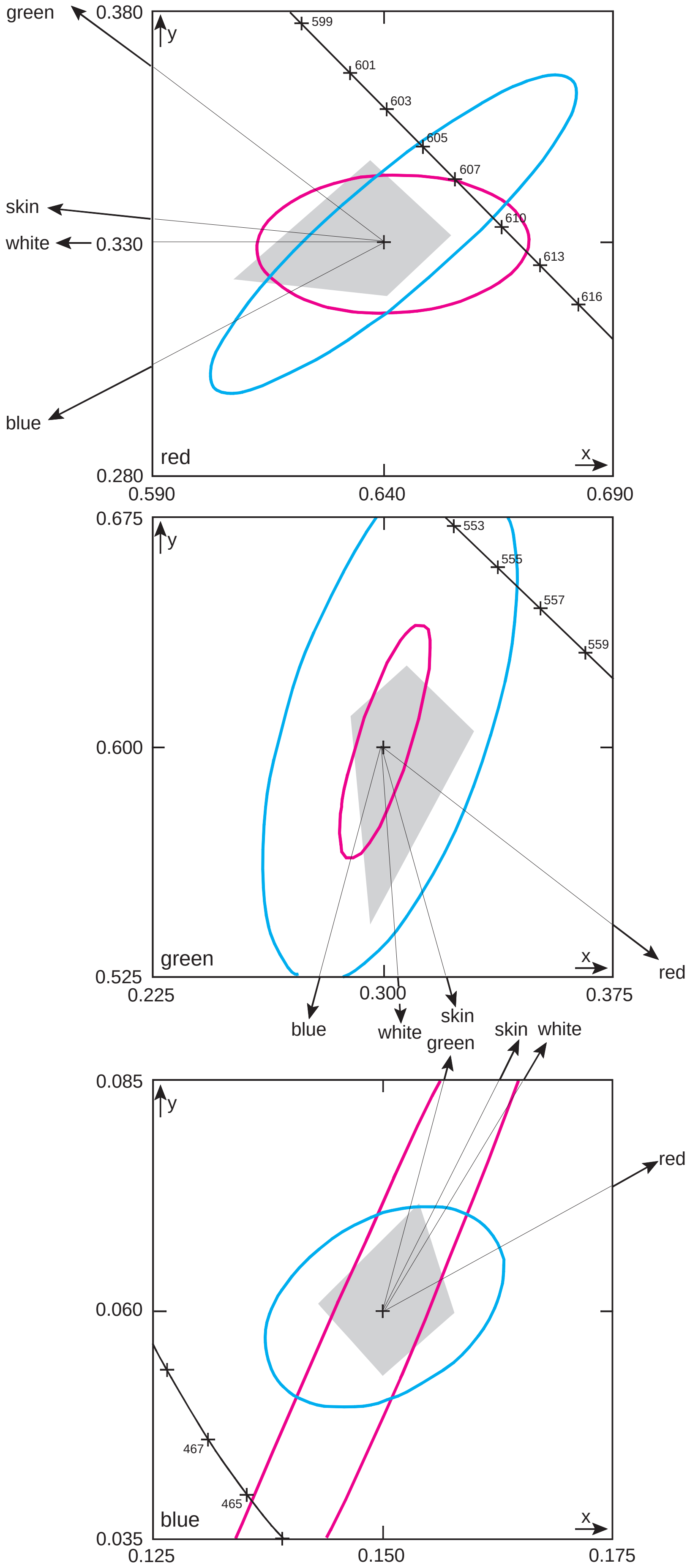


Fig. 1 - CIE 1960 jnd errors.

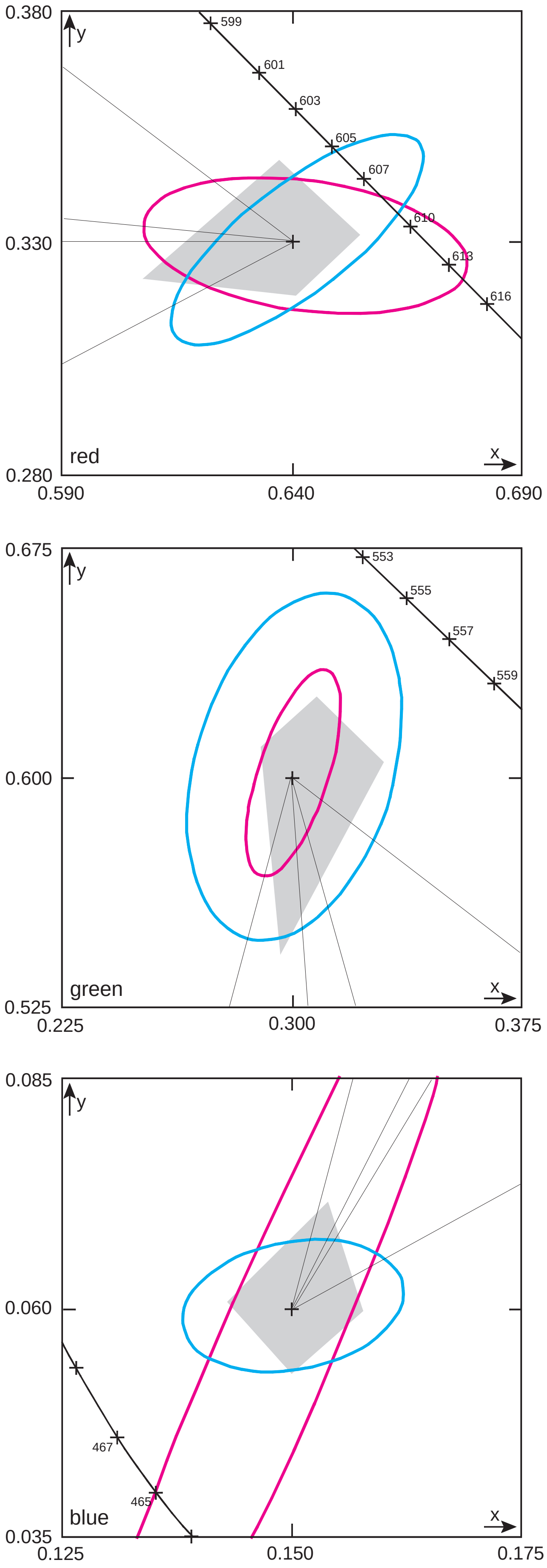


Fig. 2 - CIE 1976 jnd errors.

test colour error = 0.2 ▬

primary colour error = 3.0 ▬

EBU tolerances ▨

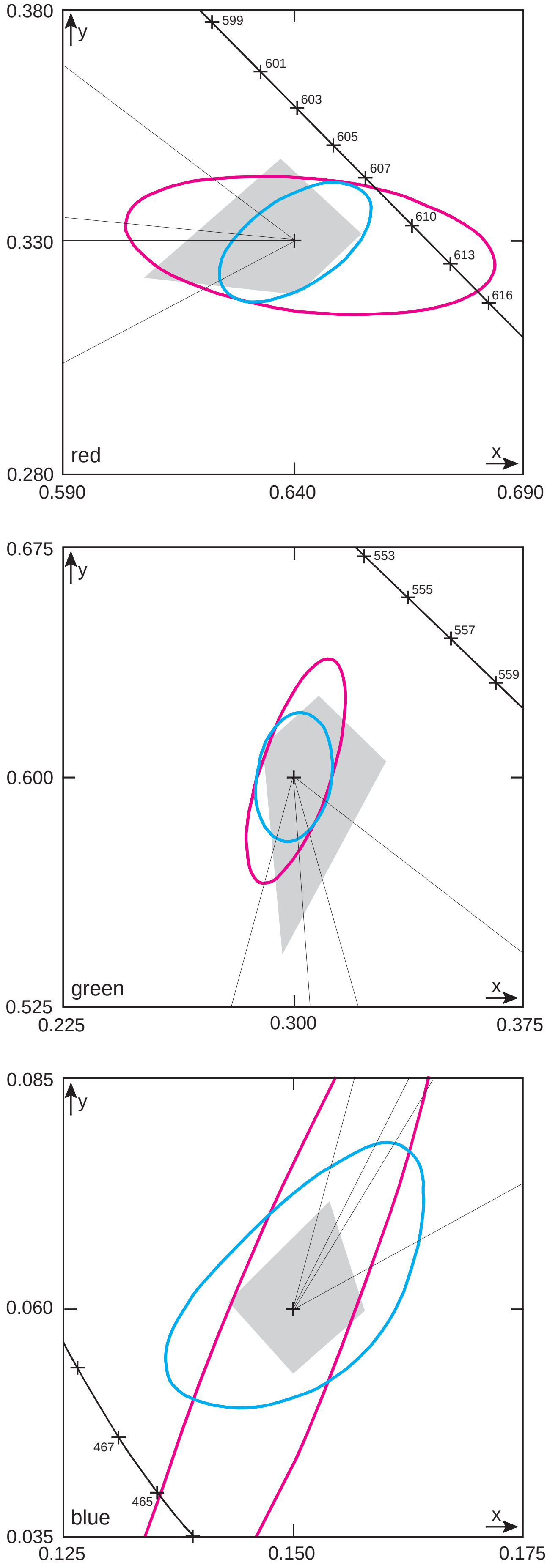


Fig. 3 - CIELUV δE errors.*

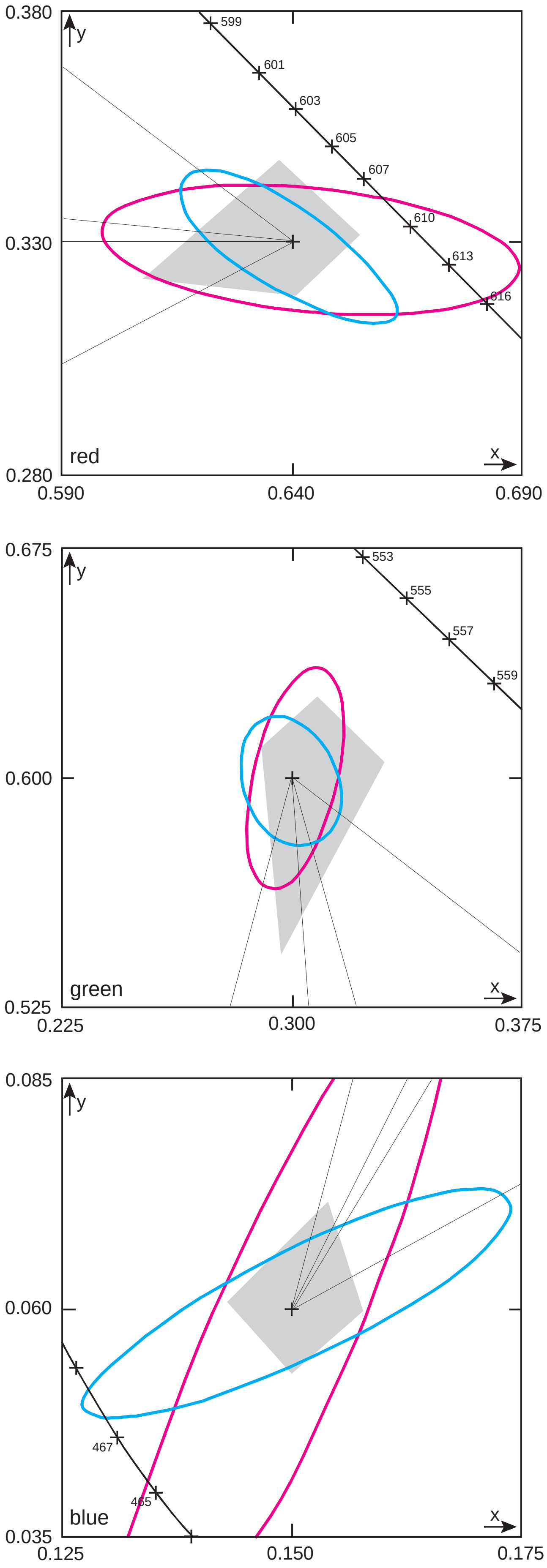
test colour error = 1.0 ━

primary colour error = 6.0 ━

EBU tolerances ▨

Fig. 4 - CIELab δE errors.*

test colour error = 0.75	🟥
primary colour error = 8.0	🟦
EBU tolerances	▨



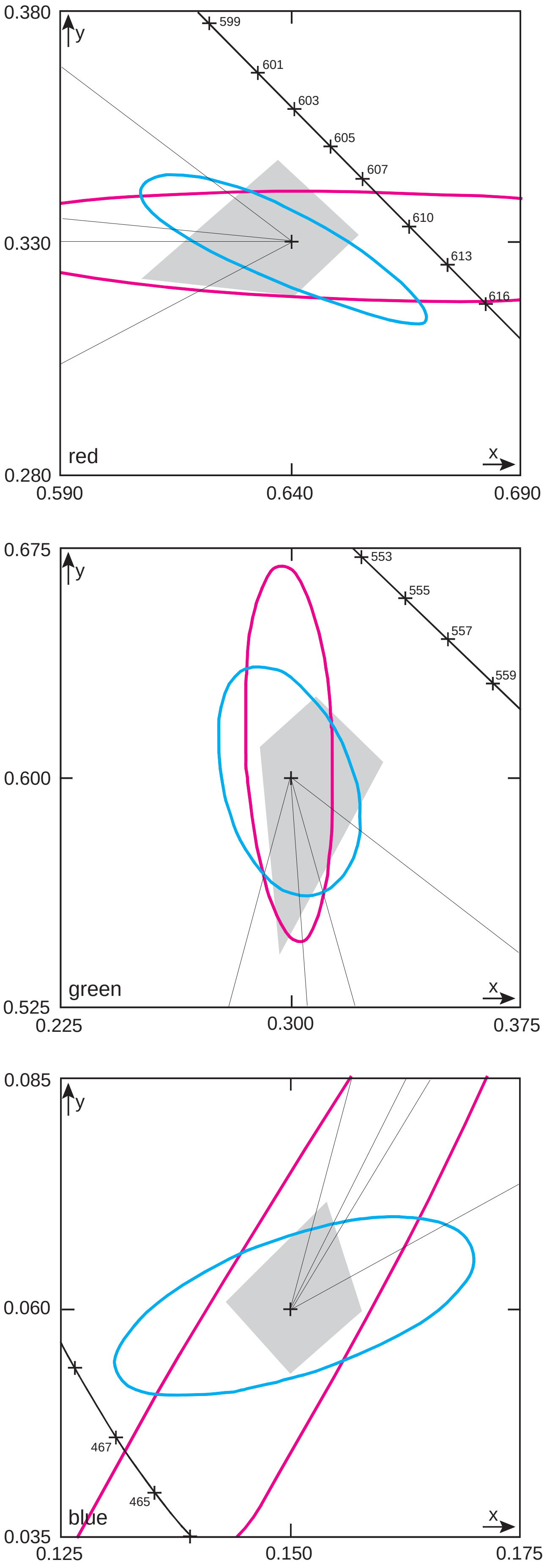


Fig. 5 - CMC(1:1)δE errors.*

test colour error = 1.0 —

primary colour error = 4.0 —

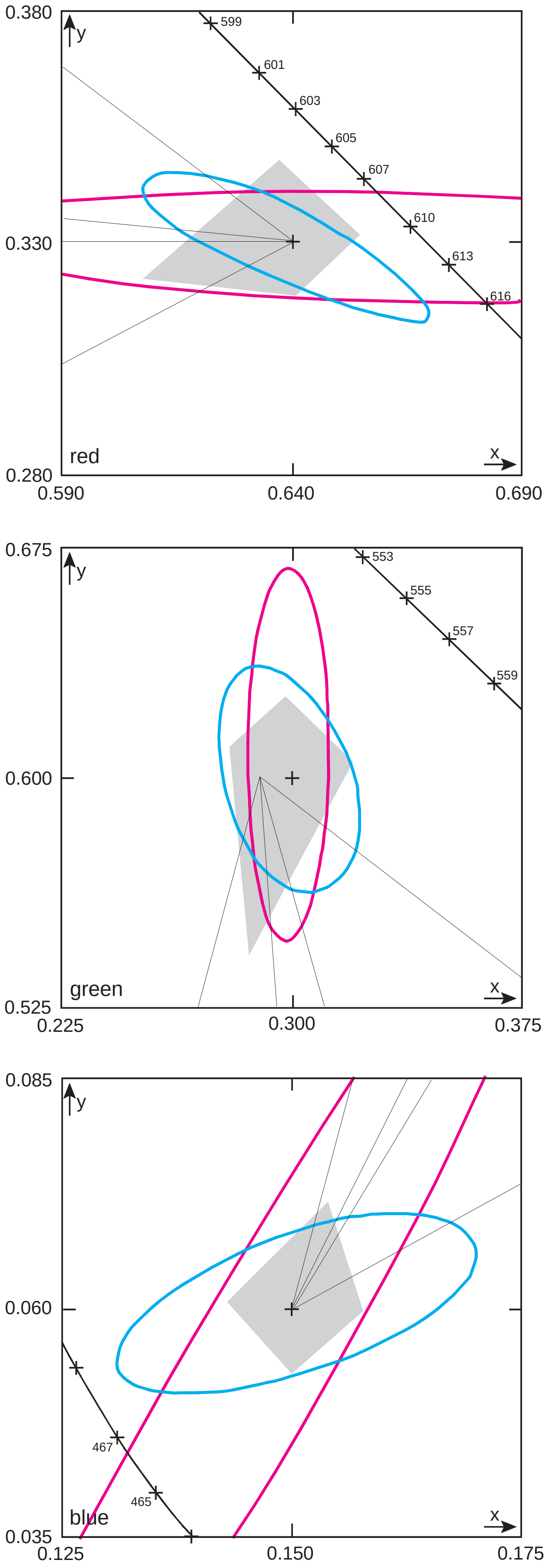
EBU tolerances ▨

Fig. 6 - CMC(1:1)δE^* errors.

test colour error = 1.0 —

primary colour error = 4.0 —

EBU tolerances ▨



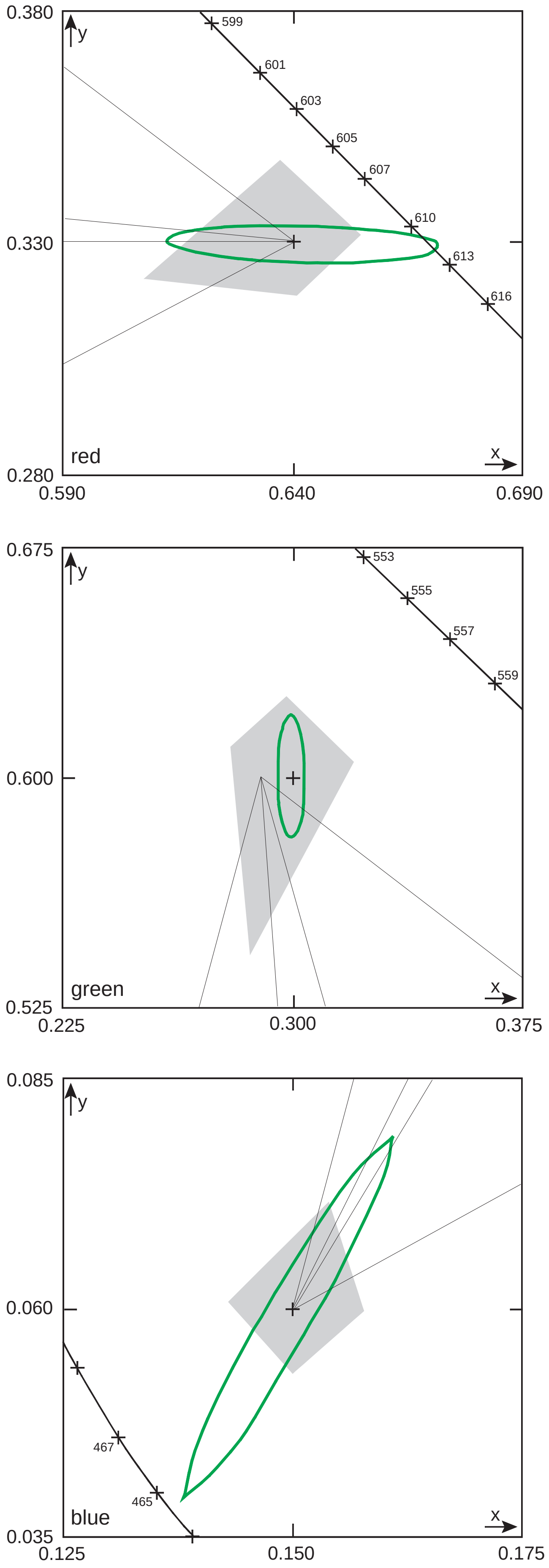


Fig. 7 - CMC(1:1)δE errors.*

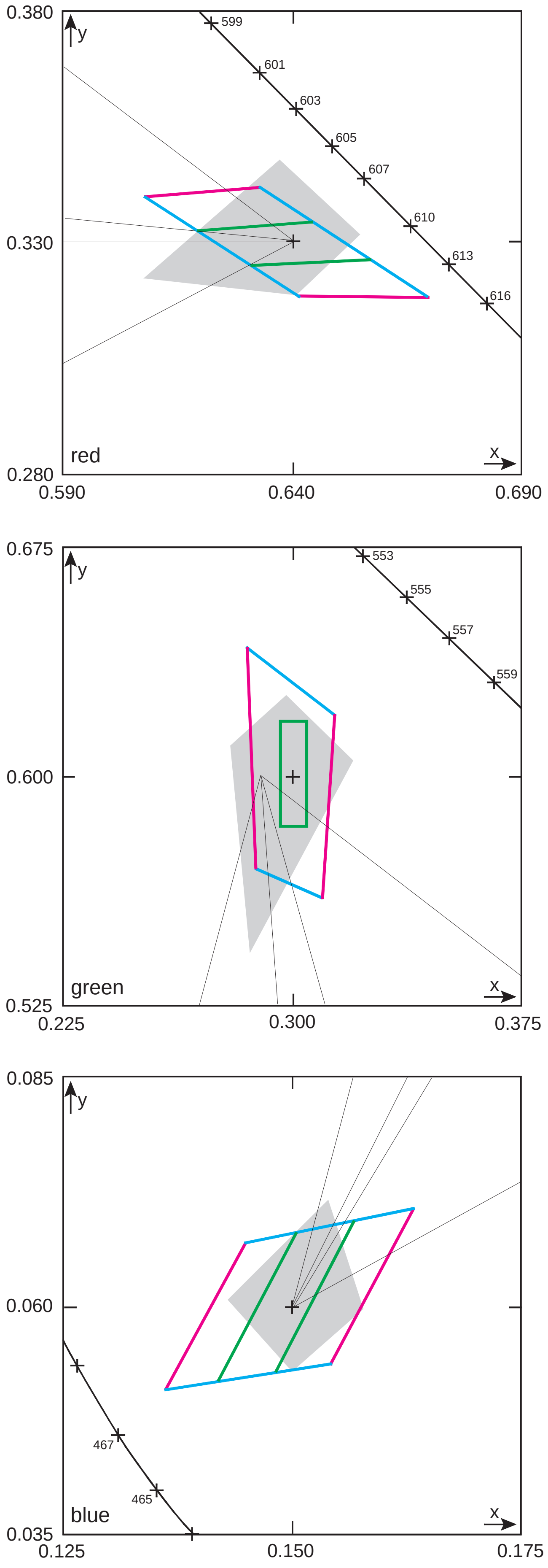


Fig. 8 - Proposed Rec. 709 inner and outer tolerance boxes.

test colour error = $\frac{1}{3}$ 🟩

test colour error = 1.0 🟥

primary colour error = 4.0 🟦

EBU tolerances ▨

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